

SYSTEM AND METHOD FOR ANALYZING AND IMAGING
THREE-DIMENSIONAL VOLUME DATA SETS USING A
THREE-DIMENSIONAL SAMPLING PROBE

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is a continuation of U.S. Application Serial No. 09/119,635 filed on July 21, 1998, which is hereby incorporated by reference. Applicants therefore, claim priority based on the filing date of U.S. Application Serial No. 09/119,635.

BACKGROUND OF THE INVENTION

Field of the Invention

[0002] The present invention relates generally to imaging of three-dimensional ("3D") volume data sets. More particularly, the present invention relates to fast visualization and analysis of very large 3D volume data sets using 3D computer graphics.

Related Art

[0003] Many fields of endeavor require the analysis and imaging of three-dimensional ("3D") volume data sets. For example, in the medical field, a CAT (computerized axial tomography) scanner or a magnetic resonance imaging (MRI) device is used to produce a "picture" or diagnostic image of some part of a patient's body. The scanner or MRI device generates a 3D volume data set that needs to be imaged or displayed so that medical personnel can analyze the image and form a diagnosis.

[0004] Three-dimensional volume data sets are also used in various fields of endeavor relating to the earth sciences. Seismic sounding is one method for exploring the subsurface geology of the earth. An underground explosion or earthquake excites seismic

waves, similar to low frequency sound waves, that travel below the surface of earth and are detected by seismographs. The seismographs record the time of arrival of the seismic waves, both direct and reflected waves. Knowing the time and place of the explosion or earthquake, the time of travel of the waves through the interior can be calculated and used to measure the velocity of the waves in the interior. A similar technique can be used for offshore oil and gas exploration. In offshore exploration, a ship tows a sound source and underwater hydrophones. Low frequency (*e.g.*, 50 Hz) sound waves are generated by, for example, a pneumatic device that works like a balloon burst. The sounds bounce off rock layers below the sea floor and are picked up by the hydrophones. In this manner, subsurface sedimentary structures that trap oil, such as faults, folds, and domes, are "mapped" by the reflected waves. The data is processed to produce volume data sets that include a reflection or seismic amplitude data value at specified (x, y, z) locations within a geographic space.

[0005] A 3D volume data set is made up of "voxels" or volume elements. Each voxel has a numeric value for some measured or calculated property, *e.g.*, seismic amplitude, of the volume at that location. One conventional approach to generating an image of a 3D volume data set is to cross-section the 3D volume data set into a plurality of two-dimensional ("2D") cross-sections or slices. The image of the 3D volume data set is then built as a composite of the 2D slices. For example, the image of the 3D volume data set is generated by stacking the 2D slices in order, back-to-front, and then composited into a complete image. The user sees the image being built layer by layer as the composite grows. Although the user can see the internal organization or structure of the volume as the composite image grows, the traditional slice and composite technique is typically

slow, particularly when very large 3D volume data sets are being used. Additionally, the slice and composite technique clutters the user's field of view with extraneous information, and interferes with the user's ability to accurately visualize and interpret features inherent in the 3D volume data set.

[0006] Computer software has been developed specifically for imaging 3D seismic data sets for the oil and gas industry. Examples of such conventional computer programs include VoxelGeo, available from Paradigm Geophysical, Houston, TX, SeisWorks and EarthCube, available from Landmark Graphics Corporation, and IESX, available from GeoQuest. Such conventional computer programs have numerous deficiencies that preclude a user from quickly and accurately visualizing and interpreting features inherent in a 3D seismic data set. Conventional computer programs for visualizing and interpreting 3D seismic data operate on the full 3D volume of seismic data. Consequently, every time a change is made, such as a change to the transparency or opacity settings, the full 3D volume of seismic data must be processed, and the image redrawn. Even when such programs are run on highly efficient graphics supercomputers, the delay or lag in re-drawing the image is perceptible to the user. For a 3D volume containing 500 megabytes of seismic data, it can take on the order of 30-45 seconds for conventional programs to re-draw the complete image (frame rate of 0.03 to 0.02 frames per second, respectively). During the 30-45 second delay time, the mind of the user loses focus on the feature of interest, making it difficult to completely and properly analyze the seismic data.

[0007] Some conventional 3D seismic interpretation programs provide the capability to visualize and interpret a piece of the full 3D volume of seismic data. The user identifies

the coordinates of the selected piece via a menu command. An image of the selected piece is drawn. The selected piece can then be rotated, if desired, at that location. However, to look at a different piece of the full 3D volume of seismic data, such as to follow a geologic feature that has been tentatively identified, the image must be interrupted, a new location or coordinates for the different piece is entered, and a new image is drawn containing the different piece. The interruption in the displayed image makes it difficult for the user to visualize any continuity between the two pieces of the full 3D volume of seismic data that have been imaged. This impedes the user's ability to interpret and identify the geologic features that are inherent in the full 3D volume of seismic data. Additionally, even though only a piece of the full 3D volume of seismic data is being visibly displayed, conventional 3D seismic interpretation programs continue processing the full 3D volume of seismic data to draw the image, thereby slowing the display of the image to the user.

[0008] Conventional 3D seismic interpretation programs provide the capability to "auto pick" and identify points that satisfy a voxel selection algorithm. However, these programs typically iterate through the full 3D volume of seismic data to identify the points that satisfy the voxel selection algorithm. This is time consuming even on a high speed graphics supercomputer. Additionally, conventional 3D seismic interpretation programs do not provide the capability to directly delete from the collection of picked voxels. The only way to "eliminate" points from the collection of picked voxels using conventional 3D seismic interpretation programs is to repeatedly adjust the selection criteria for the voxel selection algorithm until the points to be eliminated fall outside of the selection criteria for the displayed points that satisfy the voxel selection algorithm.

Each time the selection criteria is adjusted, the image must be interrupted. This iterative process is time consuming, and interferes with the visualization process of the user.

[0009] Thus, there is a need in the art for a system and method for imaging 3D volume data sets that overcomes the deficiencies detailed above. Particularly, there is a need for a system and method that re-draws images of large 3D volume data sets in response to user input at a rate sufficiently fast that the user perceives an instantaneous or real-time change in the image, without perceptible delay or lag. There is a need for a system and method that allows a user to interactively change the displayed image in a continuous manner, without interruption or perceptible delay or lag. Such a system and method would allow a user to more quickly and accurately interpret and identify features inherent in 3D volume data sets.

Summary of the Invention

[0010] The present invention is directed to a system and method for analyzing and imaging 3D volume data sets using a 3D sampling probe. In one aspect of the invention, a program storage device is provided. The program storage device is readable by a machine, and tangibly embodies a program of instructions executable by the machine to perform method steps of imaging a 3D volume defined by a data set of voxels, each voxel expressed in the form of (x, y, z, data value). The method steps comprise the following steps:

- a. creating one or more three-dimensional (3D) sampling probe(s), wherein each 3D sampling probe is a sub-volume of the 3D volume;

- b. drawing an image of the 3D sampling probe(s) for display to a user, the image comprising an intersection of the 3D sampling probe(s) and the 3D volume; and
- c. repeating drawing step (b) responsive to input from the user to move a location of the 3D sampling probe(s) within the 3D volume so that as the 3D sampling probe(s) moves through the 3D volume, the image of the 3D sampling probe(s) is re-drawn sufficiently fast to be perceived as real-time by the user, thereby enabling the user to visualize a feature defined by the data values.

[0011] In another aspect of the invention, the method steps further comprise the following step:

- d. repeating drawing step (b) responsive to input from the user to re-shape the 3D sampling probe(s) so that as the 3D sampling probe(s) is changed in shape, the image of the 3D sampling probe(s) is re-drawn sufficiently fast to be perceived as real-time by the user.

[0012] In a further aspect of the invention, the method steps further comprise identifying a seed point that is within a data set of voxels that defines an auto picking 3D sampling probe, and defining a selection criteria based on data values. Points connected to the seed point that have data values satisfying the selection criteria are identified as selected points. As the auto picking 3D sampling probe moves through the 3D volume, the image

of the auto picking 3D sampling probe contains selected points within the auto picking 3D sampling probe sub-volume, and the image is re-drawn sufficiently fast to be perceived as real-time by the user.

[0013] In yet a further aspect of the invention, the method steps further comprise defining an eraser 3D sampling probe, and defining a de-selection criteria based on data values. Points previously selected by an auto picking operation that satisfy the de-selection criteria are identified as candidates for de-selection. As the eraser 3D sampling probe moves through the 3D volume, the de-selected points are deleted from the image, and the image is re-drawn sufficiently fast to be perceived as real-time by the user.

[0014] In still a further aspect of the present invention, a method is provided for imaging a three-dimensional (3D) data volume representing a geographic space for visualization and interpretation of physical parameters of the geographic space by a user, wherein the 3D data volume is defined by a data set of voxels, each voxel expressed in the form of (x, y, z, data value), the method comprising:

- a. creating one or more three-dimensional (3D) sampling probe(s), wherein each 3D sampling probe is a sub-volume of the 3D data volume;
- b. drawing an image of the 3D sampling probe(s) for display to a user, the image comprising an intersection of the 3D sampling probe(s) and the 3D data volume; and

- c. repeating drawing step (b) responsive to input from the user to move a location of the 3D sampling probe(s) within the 3D data volume so that as the 3D sampling probe(s) moves through the 3D data volume, the image of the 3D sampling probe(s) is re-drawn sufficiently fast to be perceived as real time by the user, thereby enabling the user to visualize and interpret physical parameters in the geographic space.

[0015] In still a further aspect of the invention, a computer program product is provided that comprises a computer useable medium having computer program logic recorded thereon for enabling a processor in a computer system to image a three-dimensional (3D) seismic data volume for visualization and interpretation of geologic features by a user, the 3D seismic data volume being defined by a data set of voxels, each voxel expressed in the form of (x, y, z, seismic amplitude). The computer program product comprises: probe creating means for enabling the processor to create one or more three-dimensional (3D) sampling probe(s), each 3D sampling probe being a sub-volume of the 3D seismic data volume; image drawing means for enabling the processor to draw an image of the 3D sampling probe(s) for display to a user, the image comprising an intersection of the 3D sampling probe(s) and the 3D seismic data volume; and drawing repeating means for enabling the processor to repeatedly draw responsive to input from the user to move a location of the 3D sampling probe(s) within the 3D seismic data volume so that as the 3D sampling probe(s) moves through the 3D seismic data volume, the image of the 3D sampling probe(s) is re-drawn sufficiently fast to be perceived as real-time by the user, thereby enabling the user to visualize and interpret geologic features.

[0016] In yet a further aspect of the invention, a system is provided for imaging a three-dimensional (3D) seismic data volume for visualization and interpretation of geologic features by a user, the 3D seismic data volume being defined by a data set of voxels, each voxel expressed in the form of (x, y, z, seismic amplitude). The system comprises: means for creating one or more three-dimensional (3D) sampling probe(s), each 3D sampling probe being a sub-volume of the 3D seismic data volume; image drawing means for drawing an image of the 3D sampling probe(s) for display to a user, the image comprising an intersection of the 3D sampling probe(s) and the 3D seismic data volume; and drawing repeating means for repeatedly drawing the image of the 3D sampling probe(s) responsive to input from the user to move a location of the 3D sampling probe(s) within the 3D seismic data volume so that as the 3D sampling probe(s) moves through the 3D seismic data volume, the image of the 3D sampling probe(s) is re-drawn sufficiently fast to be perceived as real-time by the user, thereby enabling the user to visualize and interpret geologic features.

Features and Advantages

[0017] It is a feature of the present invention that, as a user interactively moves a 3D sampling probe through a 3D volume data set, the image on the surfaces of the 3D sampling probe is redrawn "on the fly" so that the user perceives the image changing in real-time with movement of the 3D sampling probe. Similarly, as a user interactively moves a 3D sampling probe through a 3D volume data set, the 3D sampling probe is volume rendered with varying degrees of transparency "on the fly" so that the user perceives the image changing in real-time with movement of the 3D sampling probe.

[0018] It is a further feature of the present invention that a user can interactively change the shape or size of a 3D sampling probe so that the image on the surfaces of the 3D sampling probe is re-drawn "on the fly" so that the user perceives the image changing in real-time with the change in shape or size of the 3D sampling probe. Similarly, a user can interactively change the shape or size of a 3D sampling probe so that the 3D sampling probe is volume rendered with varying degrees of transparency "on the fly" so that the user perceives the image changing in real time with the change in shape or size of the 3D sampling probe.

[0019] It is yet a further feature of the present invention that a user can interactively rotate a 3D sampling probe so that the image on the surfaces of the 3D sampling probe is re-drawn "on the fly" so that the user perceives the image changing in real-time with the rotation of the 3D sampling probe. Similarly, a user can interactively rotate a 3D sampling probe so that the 3D sampling probe is volume rendered with varying degrees of transparency "on the fly" so that the user perceives the image changing in real-time with the rotation of the 3D sampling probe.

[0020] It is yet a further feature of the present invention that an eraser 3D sampling probe can be created and manipulated by the user to directly delete from an image selected points that fall within a certain data value range.

[0021] It is an advantage of the present invention that a user can manipulate a 3D sampling probe to interactively traverse a 3D volume data set to continuously follow and image a feature.

[0022] It is a further advantage of the present invention that a user can interactively change the displayed image in a continuous manner, without interruption or perceptible delay or lag. This allows a user to more quickly and accurately interpret and identify features inherent in 3D volume data sets.

[0023] It is yet a further advantage of the present invention that the 3D sampling probes can be interactively re-shaped by the user to match the shape of geologic features, thereby enabling the user to better visualize and define the extent of geologic features.

[0024] A still further advantage of the present invention is that it can be used to visualize and interpret large volumes of 3D seismic data. The present invention can be used to quickly and accurately identify drilling sites. The present invention can advantageously be used to sharply reduce 3D seismic project cycle times, to boost production from existing wells, and to locate additional reserves.

Brief Description of the Figures

[0025] The file of this patent contains at least one drawing executed in color. Copies of this patent with color drawings will be provided by the Patent and Trademark Office upon request and payment of the necessary fee.

[0026] The present invention is described with reference to the accompanying drawings. In the drawings, like reference numbers indicate identical or functionally similar elements. Additionally, the left-most digit(s) of a reference number identifies the drawing in which the reference number first appears.

[0027] FIG. 1 shows one embodiment of a software or program structure for implementing the present invention;

[0028] FIG. 2 shows a block diagram of one embodiment of the 3D sampling probe program of the present invention;

[0029] FIG. 3 shows a curve illustrating opacity as a function of data value;

[0030] FIG. 4 shows a flow diagram illustrating one embodiment for implementing the present invention;

[0031] FIG. 5 shows a flow diagram of one embodiment for changing a default probe;

[0032] FIG. 6 shows a flow diagram of one embodiment for creating additional probes;

[0033] FIG. 7 shows a flow diagram of one embodiment for moving a probe;

[0034] FIG. 8 shows a flow diagram of one embodiment for re-shaping a probe;

[0035] FIG. 9 shows a flow diagram of one embodiment for rotating a probe in 3D space;

[0036] FIG. 10 shows a flow diagram of one embodiment for rotating a probe while fixed in space;

[0037] FIG. 11 shows a flow diagram of one embodiment for carrying out auto picking or seed selection;

[0038] FIG. 12 shows one embodiment of a computer system suitable for use with the present invention;

[0039] FIG. 13 shows an alternate embodiment of a computer system suitable for use with the present invention;

[0040] FIG. 14 shows further detail of an exemplary computer system suitable for use with the present invention;

[0041] FIG. 15 shows a color drawing illustrating three opaque probes of the present invention, with two of the probes intersecting each other; and

[0042] FIG. 16 shows a color drawing illustrating three probes of the present invention, a data probe, a transparent cut probe, and a volume-rendered probe.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Overview

[0043] The present invention is directed to a system and method for analyzing and imaging three-dimensional ("3D") volume data sets using a 3D sampling probe. 3D volume data sets comprise "voxels" or volume elements. Each voxel is a sample or point within a volume. Each voxel can be expressed in the form (x, y, z, data value) where "x, y, z" identifies the 3D location of the point within the volume, and "data value" is the value of some measured or calculated attribute or physical parameter at the specified point within the volume. For example, a 3D volume data set suitable for use with the present invention is 3D seismic data. Each voxel in a 3D seismic data can be expressed as (x, y, z, amplitude), with amplitude corresponding to the amplitude of reflected sound waves at the specified (x, y, z) location.

[0044] Any form of information that can be expressed in the voxel form (x, y, z, data value) is suitable for use with the present invention. In addition to seismic data, examples from the oil and gas industry include information from closely spaced well logs, gravity and magnetic fields, remote sensing data, and sidescan sonar image data. Other geologic or physical information could also include temperature, pressure, saturation, reflectivity, acoustical impedance, and velocity.

[0045] Another application for the present invention is for mining. For example, the present invention can be used to visualize and interpret geologic and geophysical data to locate mining sites, to locate and track deposits to be mined, or to locate and track geologic features such as faults that would affect mining operations. The present invention also has application for cleanup of toxic, hazardous, or other types of waste. For example, the present invention can be used to visualize and interpret data representing the geographic extent and distribution of the waste at a particular site. Such visualization and interpretation is useful for prioritizing clean-up at various sites, and for developing a clean-up plan for a particular site.

[0046] The present invention can also be used with information outside of the oil and gas industry. For example, the present invention can be used for analyzing and imaging in the medical field, where the data value element of the voxel is obtained from a CAT (computerized axial tomography) scanner or a magnetic resonance imaging (MRI) procedure.

[0047] By way of explanation and example, the present invention will be described in detail below using 3D seismic data as the 3D volume data set. It is to be understood, however, that the present invention is not limited in any way to use of 3D seismic data.

[0048] The present invention is particularly useful as a visualization tool for interpreting 3D seismic data. As used herein, the term "visualization" refers to the construction of a three-dimensional picture in the user's mind of physical or geologic features or physical parameters that are inherently present in 3D volume data sets. Such physical features or parameters are typically not apparent from conventional means of processing 3D data sets, such as scanning a series of cross-sections of the 3D volume data set, because of the mental reconstruction that needs to take place in order for a user to mentally "picture" the three-dimensional feature. Because of this mental reconstruction, it is difficult to communicate and share among users the same 3D image. For example, the same 3D mental image of the terrain will not necessarily be present in the mind of every person that reads or analyzes a two-dimensional ("2D") contour map of that terrain. Through the use of 3D computer graphics, users can visualize, and communicate and share, the same 3D image of 3D volume data sets. By visualizing 3D seismic data, a team of geologists, geophysicists, and engineers can interpret the visualized data to make exploration and production decisions, such as drilling locations and well paths.

[0049] To accomplish the visualization function, the present invention uses the computer graphics techniques of texture mapping and volume rendering. By "texture map" is meant wrapping or mapping a 2D picture or image onto a 2D or a 3D object. For example, a photograph of a person can be texture mapped onto a coffee cup.

[0050] The term "volume rendering" or "volume imaging" refers to drawing a three-dimensional object in a manner that conveys to a viewer the three-dimensional nature of the object, even though the viewer may be looking at a two-dimensional display or screen. Computer graphics technology makes use of coloring, lighting, and shading techniques to convey to the mind of the viewer what is high or low, behind or in front, light or dark, etc. The perspective or viewpoint can be changed so that the viewer can see all sides of the 3D object. Volume rendering typically includes some type of transparency/opacity ($\text{opacity} = 1 - \text{transparency}$) control so that certain parts of the 3D object are more transparent, thereby allowing a viewer to "see through" outer surfaces of an object and view its internal structures.

[0051] The present invention enables fast visualization and analysis of very large 3D volume data sets through the use of a "sampling probe", also referred to herein as a "probe" or "probe object". As explained in more detail below, the sampling probes of the present invention have numerous attributes, one of which is that they are typically created as a 3D sub-volume of the whole 3D volume data set to be visualized and analyzed.

[0052] A number of sampling probes can be created, shaped, sized, and moved interactively by the user within the whole 3D volume data set. The intersection of the sampling probe with the whole 3D volume data set is texture mapped onto the surfaces of the sampling probe, or volume rendered with varying degrees of transparency within the sampling probe. As used herein, the term "interactive" or "interactively" refers to changing or re-drawing an image in response to user input at a rate sufficiently fast that the user perceives an instantaneous or real-time change in the image, without perceptible delay or lag. In practice, a frame rate of at least about 10 to 15 frames per second is

sufficient to achieve interactive imaging as described herein. For example, as the user moves the sampling probe, such as by "clicking and dragging" with a "mouse", the user perceives the texture on the surfaces of the sampling probe changing in "real-time" with movement of the sampling probe. As the sampling probe changes shape, size, or location, there is no user-perceivable delay or lag in imaging the texture, or, with varying degrees of transparency, volume-rendered attributes. In this manner, the user can interactively move the sampling probes through the whole 3D volume, and more easily and effectively visualize and interpret the features and physical parameters that are present within the geographic space represented by the whole 3D volume data set.

System Description

[0053] The present invention may be implemented using hardware, software or a combination thereof, and may be implemented in a computer system or other processing system. One embodiment of a software or program structure **100** for implementing the present invention is shown in FIG. 1. At the base of program structure **100** is an operating system **102**. Suitable operating systems **102** include, for example, the UNIX@ operating system, or Windows NT@ from Microsoft Corporation, or other operating systems as would be apparent to one of skill in the relevant art.

[0054] Menu and windowing software **104** overlays operating system **102**. Menu and windowing software **104** is used to provide various menus and windows to facilitate interaction with the user, and to obtain user input and instructions. Menu and windowing software **104** can include, for example, Microsoft Windows™, X Window System™ (registered trademark of Massachusetts Institute of Technology), and MOTIF™

(registered trademark of Open Software Foundation Inc.). As would be readily apparent to one of skill in the relevant art, other menu and windowing software could also be used.

[0055] A basic graphics library **106** overlays menu and windowing software **104**. Basic graphics library **106** is an application programming interface (API) for 3D computer graphics. The functions performed by basic graphics library **106** include, for example, geometric and raster primitives, RGBA or color index mode, display list or immediate mode, viewing and modeling transformations, lighting and shading, hidden surface removal, alpha blending (translucency), anti-aliasing, texture mapping, atmospheric effects (fog, smoke, haze), feedback and selection, stencil planes, and accumulation buffer.

[0056] A particularly preferred basic graphics library **106** is OpenGL[®], available from Silicon Graphics, Inc. ("SGI"), Mountain View, California. The OpenGL[®] API is a multi platform industry standard that is hardware, window, and operating system independent. OpenGL[®] is designed to be callable from C, C++, FORTRAN, Ada and Java programming languages. OpenGL[®] performs each of the functions listed above for basic graphics library **106**. Some commands in OpenGL[®] specify geometric objects to be drawn, and others control how the objects are handled. All elements of the OpenGL[®] state, even the contents of the texture memory and the frame buffer, can be obtained by a client application using OpenGL[®]. OpenGL[®] and the client application may operate on the same or different machines because OpenGL[®] is network transparent. OpenGL[®] is described in more detail in the OpenGL[®] Programming Guide (ISBN: 0-201-63274-8) and the OpenGL[®] Reference Manual (ISBN: 0-201-63276-4), the entirety of both of which are incorporated herein by reference.

[0057] Visual simulation graphics library **108** overlays basic graphics library **106**. Visual simulation graphics library **108** is an API for creating real-time, multi-processed 3D visual simulation graphics applications. Visual simulation graphics library **108** provides functions that bundle together graphics library state control functions such as lighting, materials, texture, and transparency. These functions track state and the creation of display lists that can be rendered later.

[0058] A particularly preferred visual simulation graphics library **108** is IRIS Performer, available from SGI in Mountain View, California. IRIS Performer supports the OpenGL[®] graphics library discussed above. IRIS Performer includes two main libraries, *libpf* and *libpr*, and four associated libraries, *libpfdu*, *libpfdb*, *libpfui*, and *libpfutil*.

[0059] The basis of IRIS Performer is the performance rendering library *libpr*, a low-level library providing high speed rendering functions based on GeoSets and graphics state control using GeoStates. GeoSets are collections of drawable geometry that group same-type graphics primitives (*e.g.*, triangles or quads) into one data object. The GeoSet contains no geometry itself, only pointers to data arrays and index arrays. Because all the primitives in a GeoSet are of the same type and have the same attributes, rendering of most databases is performed at maximum hardware speed. GeoStates provide graphics state definitions (*e.g.*, texture or material) for GeoSets.

[0060] Layered above *libpr* is *libpf*, a real-time visual simulation environment providing a high-performance multi-process database rendering system that optimizes use of multiprocessing hardware. The database utility library, *libpfdu*, provides functions for defining both geometric and appearance attributes of 3D objects, shares state and

materials, and generates triangle strips from independent polygonal input. The database library *libpfdb* uses the facilities of *libpfdu*, *libpf*, and *libpr* to import database files in a number of industry standard database formats. The *libpfui* is a user interface library that provides building blocks for writing manipulation components for user interfaces (C and C++ programming languages). Finally, the *libpfutil* is the utility library that provides routines for implementing tasks such as MultiChannel Option support and graphical user interface (GUI) tools.

[0061] An application program that uses IRIS Performer and OpenGL[®] API typically carry out the following steps in preparing for real-time 3D visual simulation.

1. Initialize IRIS Performer.
2. Specify number of graphics pipelines, choose the multiprocessing configuration, and specify hardware mode as needed.
3. Initialize chosen multiprocessing mode.
4. Initialize frame rate and set frame-extend policy.
5. Create, configure, and open windows as required.
6. Create and configure display channels as required.

[0062] Once the application program has created a graphical rendering environment by carrying out steps 1 through 6 above, then the application program typically iterates through a main simulation loop once per frame.

7. Compute dynamics, update model matrices, etc.
8. Delay until the next frame time.
9. Perform latency critical viewpoint updates.
10. Draw a frame.

[0063] A 3D sampling probe program **110** of the present inventions overlays visual simulation graphics library **108**. Program **110** interacts with, and uses the functions carried out by, each of visual simulation and graphics library **108**, basic graphics library **106**, menu and windowing software **104**, and operating system **102** in a manner known to one of skill in the relevant art.

[0064] 3D sampling probe program **110** of the present invention is preferably written in an object oriented programming language to allow the creation and use of objects and object functionality. A particularly preferred object oriented programming language is C++. In carrying out the present invention, program **110** creates one or more probe "objects". As noted above, the probe objects created and used by program **110** are also referred to herein as sampling probes or probes. Program **110** manipulates the probe objects so that they have the following attributes.

[0065] A probe corresponds to a sub-volume of a larger 3D volume. Particularly, a probe defines a sub-set that is less than the complete data set of voxels for a 3D volume data set. A probe could be configured to be equal to or coextensive with the complete data set of voxels for a 3D volume data set, but the functionality of the present invention is best carried out when the probe corresponds to a sub-volume and defines a sub-set that is less than the complete data set of voxels for a 3D volume data set. For example, a 3D volume data set of seismic data can contain from about 500 ME (megabytes) to about 10 GB (gigabytes) or more of data. A 2,500 square kilometer geographic space of typical 3D seismic data contains about 8 GB of data. A probe of the present invention for a 500 ME seismic data set would preferably contain about 10-20 ME of data.

[0066] By using probes that are a sub-volume of the larger 3D volume, the quantity of data that must be processed and re-drawn for each frame of an image is dramatically reduced, thereby increasing the speed with which the image can be re-drawn. The volume of a three-dimensional cube is proportional to the third power or "cube" of the dimensions of the three-dimensional cube. Likewise, the quantity of data in a 3D volume data set is proportional to the third power or "cube" of its size. Therefore, the quantity of data in a sub-volume of a larger 3D volume will be proportional to the "cubed root" ($\sqrt[3]{}$) of the quantity of data in the larger 3D volume. As such, the quantity of data in a probe of the present invention will be proportional to the "cubed root" ($\sqrt[3]{}$) of the quantity of data in the 3D volume of which it is a sub-volume. By only having to process the sub-set of data that relates to the sub-volume of the probe, the present invention can re-draw an image in response to user input at a rate sufficiently fast that the user perceives an instantaneous or real-time change in the image, without perceptible delay or lag.

[0067] The probes of the present invention can be interactively changed in shape and/or size, and interactively moved within the larger 3D volume. The outside geometry or surfaces of a probe can be interactively drawn opaque or texture mapped while the probe is being changed in shape and/or size or while the probe is being moved. The probe can be drawn or volume rendered with varying degrees of transparency while the probe is being changed in shape and/or size or moved, thereby revealing the internal structures or features of the probe.

[0068] The 3D sampling probes of the present invention can have any shape, including rectangular shapes having one or more right angles and non-rectangular shapes having no right angles. The 3D sampling probes of the present invention can have orthogonal or

perpendicular planes as outer surfaces (*e.g.*, squares and rectangles), parallel planes as outer surfaces (*e.g.*, parallelograms), or curved outer surfaces (*e.g.*, spheres, ovals, or cylinders). The present invention is not limited to 3D sampling probes of any particular shape. The 3D sampling probes of the present invention can have arbitrary shapes, such as the shape of a geologic feature identified by a user. For example, as a user moves the 3D sampling probe through a 3D volume of seismic data, a geologic feature may be visualized and identified by the user. The 3D sampling probe can be interactively re-shaped by the user to match the shape of the geologic feature, thereby enabling the user to better visualize and define the extent of that geologic feature.

[0069] A probe can be used to cut into another probe, and the intersection of the two probes can be imaged. A probe can be used to highlight data in accordance with a seed selection algorithm. A probe can also be used to "erase" or delete data in accordance with a seed de-selection algorithm. These attributes will be explained in more detail below.

[0070] FIG. 2 shows a block diagram of one embodiment of 3D sampling probe program **110**. Program **110** includes a User Interface Module (UIM) **210**, a Graphics Processing Module (GPM) **220**, and a Volume Sampling Module (VSM) **230**. A 3D volume data set is illustrated as data volume **240**, also referred to herein as a 3D volume. UIM **210** and GPM **220** communicate via a bi-directional pathway **212**. GPM **220** sends instructions and requests for data to VSM **230** via pathway **222**. UIM **210** sends instructions and requests to VSM **230** via pathway **214**. UIM **210** interacts with data volume **240** through pathway **216**.

[0071] Voxel data from data volume **240** is transferred to VSM **230** via data pathway **234**. VSM **230** transfers data to GPM **220** via data pathway **232**. Data volume **240** stores the 3D volume data set in a manner well known to one of skill in the relevant art. For example, the format for data volume **240** can consist of two parts, a volume header followed by the body of data that is as long as the size of the data set. The volume header typically contains information, in a prescribed sequence, such as the file path (location) of the data set, size, dimensions in the x, y, and z directions, annotations for the x, y, and z axes, annotations for the data value, etc. The body of data is a binary sequence of bytes; one or more bytes per data value, that can be ordered in the following manner. The first byte is the data value at volume location $(x, y, z)=(0,0,0)$. The second byte is the data value at volume location $(1,0,0)$, the third byte is the data value at volume location $(2,0,0)$, etc. When the x dimension is exhausted, then the y dimension is incremented, and finally the z dimension is incremented. The present invention is not limited in any way to a particular data format for data volume **240**.

[0072] User Interface Module **210** handles the user interface to receive commands, instructions, and input data from the user. UIM **210** interfaces with the user through a variety of menus through which the user can select various options and settings, either through keyboard selection or through one or more user-manipulated input devices, such as a "mouse," or a 3D pointing device. UIM **210** receives user input as the user manipulates the input device to move, size, shape, etc. a 3D sampling probe.

[0073] The primary functions carried out by UIM **210** will now be described. UIM **210** inputs from the user the identification of one or more 3D volume data sets (represented by data volume **240**) to use for imaging and analysis. When a plurality of data volumes

are used, the data value for each of the plurality of data volumes represents a different physical parameter or attribute for the same geographic space. By way of example, a plurality of data volumes could include a geology volume, a temperature volume, and a water-saturation volume. The voxels in the geology volume can be expressed in the form (x, y, z, seismic amplitude). The voxels in the temperature volume can be expressed in the form (x, y, z, Qq. The voxels in the water-saturation volume can be expressed in the form (x, y, z, %saturation). The physical or geographic space defined by the voxels in each of these volumes is the same. However, for any specific spatial location (xo, yo, zo), the seismic amplitude would be contained in the geology volume, the temperature in the temperature volume, and the water-saturation in the water-saturation volume.

[0074] UIM **210** inputs from the user information to create one or more 3D sampling probes. Such information includes size, shape, and initial location of the probe. Such information can also include imaging attributes such as color, lighting, shading, and transparency (or opacity). By adjusting opacity as a function of data value, certain portions of the data volume are more transparent, thereby allowing a viewer to see through surfaces. An exemplary opacity curve **300** is shown in FIG. 3. Opacity curve **300** illustrates opacity (I-transparency) as a function of data value. As would be readily apparent to one skilled in the art, data values with greater opacity (less transparency) will mask the imaging or display of data values with lower opacity (more transparency). Conversely, data values will less opacity and greater transparency will permit the imaging or display of data values with greater opacity and lower transparency.

[0075] UIM **210** receives input from the user for sizing and shaping the 3D sampling probes. As described in more detail below, in a preferred embodiment of the present

invention, the user changes the shape and/or size of a probe by clicking onto "sizing tabs" on the probe, and making changes in the dimensions of the probe in one or more directions. UIM **210** receives input from the user to move the position or location of a 3D sampling probe within the data volume. In a preferred embodiment, a user manipulates a mouse to "click" onto a surface of the probe to be moved, and then moves the mouse to move the probe throughout the geographic space defined by the data volume.

[0076] UIM **210** receives input from the user to carry out "auto picking" processes. In an auto picking process, data points (voxels) are selected based upon a selection algorithm. In a preferred embodiment, the selection algorithm is based upon a seed point within the 3D data volume. The selection algorithm then selects data points that: (i) satisfy the selection criteria or algorithm (*e.g.*, have a data value within a specified filter range); and (ii) have a connectivity with or are connected to the seed point. Through UIM **210**, the user is prompted to identify a seed point within the 3D volume, and to identify a filter range of data values used by the selection algorithm to "pick" the selected points. Preferably, the seed point is within one of the 3D sampling probes.

[0077] UIM **210** also receives input from the user regarding the content of the displayed image. For example, the user can preferably select the content of the displayed image. The content of the displayed image could include only the 3D sampling probe, *i.e.*, its intersection with the 3D volume. Additionally, the 3D sampling probe could be displayed either with or without a bounding box that defines the outer geometry of the probe. Alternatively, the displayed image could include the 3D sampling probe, as well as the data that occupies the background xz, yz, and xy planes, and/or the data occupies the 3D volume outside of the 3D sampling probe(s) being displayed.

[0078] To carry out the foregoing functions, UIM **210** sends a request to Volume Sampling Module **230** to load or attach those 3D volume data sets identified by the user. UIM **210** communicates via pathway **212** with Graphics Processing Module **220** that carries out the display and imaging.

[0079] The primary functions carried out by GPM **220** will now be described. GPM **220** processes data for imaging of 3D sampling probes with the color, lighting, shading, transparency, and other attributes selected by the user. To do so, GPM **220** uses the functions available through basic graphics library **106** and visual simulation graphics library **108** described above. The user can select (through UIM **210**) to display only the one or more 3D sampling probes that have been created. Alternatively, the user can select to display one or more 3D sampling probes, as well as the 3D data volume outside of the probes, i.e. voxels within the 3D volume that do not intersect any of the 3D sampling probes that are being displayed. 3D sampling probes that are being displayed are referred to herein as "active probes".

[0080] GPM **220** processes the re-shaping and move requests that are received by UIM **210** from the user. GPM **220** draws the re-shaped 3D sampling probe in accordance with the user-selected attributes (color, lighting, shading, transparency, etc.). As the user inputs a change in shape for a 3D sampling probe, the image with selected attributes is re-drawn sufficiently fast to be perceived as real-time by the user. Similarly, GPM **220** draws the 3D sampling probe in the new position or location in accordance with the user-selected attributes (color, lighting, shading, transparency, etc.). As the user moves the 3D sampling probe through the 3D volume, the image of the 3D sampling probe with selected attributes is re-drawn sufficiently fast to be perceived as real-time by the user.

[0081] GPM **220** processes "auto picking" requests that are received by UIM **210**. GPM **220** will image selected points within the 3D volume in accordance with the selection algorithm. Alternatively, GPM **220** will "erase" selected points within the 3D volume in accordance with the selection algorithm.

[0082] To carry out the foregoing functions, GPM **220** communicates via pathway **212** with UIM **210** so that the information requested by the user is imaged or displayed with the selected attributes. GPM **220** obtains the needed data from data volume **240** by sending a data request via pathway **222** to Volume Sampling Module (VSM) **230**.

[0083] The primary function of VSM **230** is to extract the appropriate data from data volume **240** at the request of GPM **220**. VSM **230** receives requests for data from GPM **220** via pathway **222**. VSM **230** extracts the required data from data volume **240** and transfers the data to GPM **220** via data pathway **232** for processing and display. VSM **230** also receives instructions from UIM **210** via pathway **214** to load or attach the 3D data volumes identified by the user.

[0084] Turning now to FIG. 4, a flow diagram **400** illustrating one embodiment for implementing the present invention is shown. A start up or initialization process is shown in a step **402**. In step **402**, the user specifies the one or more data volumes (**240**) to be used. The specified 3D volume data sets are loaded from disk into main memory (a description of hardware suitable for carrying out the present invention will be described in more detail below). A default 3D sampling probe is created, and drawn. The default 3D sampling probe is a sub-volume of the specified 3D volume(s) of arbitrary size and

shape. The present invention is not limited to any particular size or shape for the default 3D sampling probe.

[0085] By way of example of the present invention, the default 3D sampling probe can be a square (having equal dimensions in the x, y, and z directions). To draw the square default 3D sampling probe, the bounding geometry is first drawn with one edge of the bounding geometry located on the z axis. Data is then extracted from data volume **240** by VSM **230** to draw the image of the intersection of the square default 3D sampling probe with the 3D volume (data volume **240**). Particularly, data is extracted that corresponds to the intersection of the square default 3D sampling probe with the 3D volume in the xz, yz, and xy planes. This data is then sent by VSM **230** to GPM **220** so that it can be texture mapped onto the planes of the bounding box to provide an image of the square default 3D sampling probe.

[0086] In one embodiment of the present invention, the data that occupies the background xz, yz, and xy planes themselves, as well as the data that occupies the 3D volume outside of the default 3D sampling probe, are also imaged or displayed (in addition to the default 3D sampling probe) during start up step **402**. Alternatively, start up step **402** can be carried out so that the data that occupies the background xz, yz, and xy planes, or the data that occupies the 3D volume outside of the default 3D sampling probe, is not displayed or imaged. Preferably, the present invention is carried out so that the user can selectively display, or not display, the data that occupies the background xz, yz, and xy planes, as well as the data that occupies the 3D volume outside of the active probes.

[0087] In a step **404**, UIM **210** is waiting to respond to user input or request. User input is received through a user input device suitable for use with a computer, including but not limited to, a keyboard, mouse, joystick, trackball, rollerball, roller point, or other type of suitable pointing device, etc. Preferably, the user input device comprises a mouse or other similar device that enables the user to "click" on a particular displayed image, and "drag" that displayed image to another location. Such a user input device allows a user to move and re-shape displayed probes. Such a user input device also allows a user to activate drop-down menus, and to select the various options for the color, shading, lighting, and transparency attributes. A keyboard can also be used for entering information relating to the selected attributes.

[0088] Reference numeral **406** refers generally to a plurality of functions that can be carried out by the present invention. These functions can be carried out individually or simultaneously, depending upon input from the user. For example, a probe can be moved (function **430**) and rotated (function **450**) simultaneously. While the functions identified by reference numeral **406** are being carried out, the image of the 3D sampling probes is being re-drawn sufficiently fast to be perceived as real-time by the user. Each of the functions identified by reference numeral **406** will now be described.

[0089] If a user wants to change the default probe, then function **410** is carried out. The steps for carrying out function **410** are shown in FIG. 5 by way of flow diagram connector 5A. In a step **502**, the changes to the default probe are input by UIM **210** from the user. For example, the changes to the default probe can be to the shape or size, the location, or the attributes such as color, shading, lighting, and transparency.

[0090] In a step 504, UIM **210** sends a request to GPM **220** to draw the changed default probe. In a step 506, GPM **220** requests data for the changed default probe from VSM **230**. In making this request, GPM **220** would invoke function **430** if it was necessary to move the default probe, function **440** to re-shape the default probe, and functions **450** or **460** to rotate the default probe. The foregoing functions will be described in more detail below.

[0091] The data that will be extracted from data volume **240** by VSM **230** in response to the request made by GPM **220** in step 506 will depend upon attributes that have been selected by the user. If the opacity settings selected by the user are such that all data values are opaque, then the data extracted by VSM **230** will be limited to the surfaces of the changed default probe. Because of the selected opacity, it will not be possible for the user to see inside the changed default probe, so only the data corresponding to the surfaces or outside of the changed default probe will be extracted by VSM **230**. In a step 508, GPM **220** processes the data extracted by VSM **230** for the surfaces of the changed default probe, and draws the changed default probe by texture mapping onto the surfaces in accordance with the attributes selected by the user. By extracting only the data that can be seen by the user, the image of the changed default probe can be drawn more quickly because less data needs to be processed, *i.e.*, the data corresponding to the "inside" of the changed default probe is not processed.

[0092] Alternatively, if the opacity settings selected by the user are such that some of the data values are opaque and some of the data values are transparent, then the data extracted by VSM **230** will include the data corresponding to the entire volume of the changed default probe. Because of the selected opacity and transparency, it will be

possible for the user to see inside the changed default probe, so data corresponding to the entire volume of the changed default probe will be extracted by VSM **230**. In such a situation, GPM **220** processes the data extracted by VSM **230** in step 508, and draws the changed default probe by volume rendering in accordance with the attributes selected by the user.

[0093] If a user wants to create additional probes, then function **420** is carried out. The present invention is not limited to any particular number of active probes. The steps for carrying out function **420** are shown in FIG. 6 by way of flow diagram connector 6A. In a step 602, the shape, size, location, attributes, etc. for the additional probes are input by UIM **210** from the user. In a step 604, UIM **210** sends a request to GPM **220** to draw the additional probes.

[0094] In a step 606, GPM **220** requests data for the additional probes from VSM **230**. In a manner similar to that described above for changing the default probe, the data that is extracted from 3D or data volume **240** by VSM **230** will depend upon the opacity selected by the user for the additional probes. If the opacity settings selected by the user are such that all data values for the additional probes are opaque, then the data extracted by VSM **230** will be limited to the surfaces of the additional probes. Alternatively, if the opacity settings selected by the user for the additional probes are such that some of the data values are opaque and some of the data values are transparent, then the data extracted by VSM **230** will include the data corresponding to the entire volumes of the additional probes. In this manner, the additional probes can be drawn more quickly by minimizing the quantity of data that must be processed.

[0095] In a step 608, GPM **220** processes the data extracted by VSM **230** for the additional probes, and draws the additional probes in accordance with the attributes selected by the user, either by texture mapping onto the surfaces of the additional probes, or by volume rendering the entire volume of the additional probes.

[0096] If a user wants to move a probe, then function **430** is carried out. The steps for carrying out function **430** are shown in FIG. 7 by way of flow diagram connector 7 A. In a step 702, the new location for the probe is input by UIM **210** from the user. In a preferred embodiment of the present invention, the user inputs the new location of the probe by clicking a mouse or other type of suitable user input device to snap a pointer onto a surface of the probe to be moved. The user changes the location of the probe by moving the mouse or other suitable user input device in any direction, thereby dragging the probe along a trajectory.

[0097] In a step 704, UIM **210** sends a move request to GPM **220** to draw the probe at the new location. GPM **220** requests data for the new location of the probe from VSM **230**. In a manner similar to that described above, the data that is extracted from data volume **240** by VSM **230** will depend upon the opacity selected by the user for the probe being moved. If the opacity settings selected by the user are such that all data values for the probe being moved are opaque, then the data extracted by VSM **230** will be limited to the surfaces of the probe being moved. Alternatively, if the opacity settings selected by the user for the probe being moved are such that some of the data values are opaque and some of the data values are transparent, then the data extracted by VSM **230** will include the data corresponding to the entire volume of the probe being moved. In this manner, the

probe can be drawn at its new location more quickly by minimizing the quantity of data that must be processed.

[0098] In a step 708, GPM **220** processes the data extracted by VSM **230** for the probe being moved, and draws the probe at its new location in accordance with the attributes selected by the user, either by texture mapping onto the surfaces of the probe being moved, or by volume rendering the entire volume of the probe being moved.

[0099] As the user moves the probe, for each new location of the probe, steps 702 through 708 are repeated at a rate sufficiently fast that the user perceives the image of the probe, with texture mapping or volume rendering as appropriate, changing in "real-time" with movement of the probe. The image is being re-drawn at a frame rate sufficiently fast to be perceived as real-time by the user.

[00100] If a user wants to re-shape a probe, then function **440** is carried out. As used herein, the term "re-shape" refers to any change in dimension of a 3D sampling probe in any direction. The shape of a 3D sampling probe can be changed, or re-shaped, for example, by changing the size in one or more directions, such as by changing a square probe into a rectangular probe by increasing the size of the probe in the x direction, and decreasing the size of the probe in the y direction. As another example, the shape of a 3D sampling probe can be changed by changing the shape from spherical to rectangular. As yet another example, a square 3D sampling probe (equal dimensions in the x, y, and z directions) can be re-shaped in accordance with the present invention to be a larger or smaller square-shaped probe by changing the size equally in each of the x, y, and z directions. The re-shaped probe also has a square shape, but as a larger or smaller square.

[00101] The steps for carrying out function **440** are shown in FIG. 8 by way of flow diagram connector SA. In a step 802, the new shape and/or size for the probe is input by UIM **210** from the user. In a preferred embodiment of the present invention, the user inputs the new shape of a probe by clicking a mouse or other type of suitable user input device to snap a pointer onto a "sizing tab" of the probe to be re-shaped. As used herein, a "sizing tab" refers to a designated area on a surface of the probe. Such a designated area is preferably displayed in a color that is different from the colors being used to display the features or physical parameters of the 3D, volume data set. When the pointer is snapped to the sizing tab, manipulation of the mouse or user input device changes the dimensions or proportions of the surface on which the sizing tab is located. When the desired size or shape is reached, the user again clicks the mouse or user input device to release the pointer from the sizing tab. Sizing tabs are illustrated in FIGS. 15 and 16. The sizing tabs are the small green squares that appear on the surfaces of the probes, along the bounding geometry of the probes. The location of the sizing tabs is not limited to the bounding geometry of the probes. The user changes the shape of the probe by clicking the mouse or other suitable user input device onto a sizing tab, moving the mouse until the surface being changed has the desired shape, and then releasing the mouse from the sizing tab. This process can be repeated, if necessary, using other sizing tabs on the probe until the probe is re-shaped to the desired shape.

[00102] It would be readily apparent to one of skill in the relevant art how to implement such a sizing tab for re-shaping the probes of the present invention. It is to be understood, however, that the present invention is not limited to the use of sizing tabs for re-shaping probes, and other suitable methods can be used. For example, the user could select from a

number of pre-set shapes (*e.g.*, squares, rectangle, cylinders, spheres) by activating a drop-down menu, or by scrolling through the shapes by repeatedly clicking a mouse.

[00103] In a step 804, UIM **210** sends a re-shape request to GPM **220** to draw the re-shaped probe. In a step 806, it is determined whether more data is needed to draw the re-shaped probe. For example, if the re-shaped probe is of a shape and size that "fits inside" the existing probe, then no more data is needed, and processing continues at a step 810. Alternatively, if the reshaped probe is of a shape and size that falls at least partially outside of the existing probe, then, in a step 808, GPM **220** requests the data needed for the re-shaped probe from VSM **230**. In a manner similar to that described above, the data that is extracted from 3D or data volume **240** by VSM **230** will depend upon the opacity selected by the user for the probe being re-shaped. If the opacity settings selected by the user are such that all data values for the probe being re-shaped are opaque, then the data extracted by VSM **230** will be limited to the surfaces of the probe being re-shaped. Alternatively, if the opacity settings selected by the user for the probe being re-shaped are such that some of the data values are opaque and some of the data values are transparent, then the data extracted by VSM **230** will include the data corresponding to the entire volume of the probe being re-shaped. In this manner, the probe can be drawn with its new shape more quickly by minimizing the quantity of data that must be processed.

[00104] In step 810, GPM **220** processes the data extracted by VSM **230** for the probe being re-shaped, and draws the probe with its new shape in accordance with the attributes selected by the user, either by texture mapping onto the surfaces of the probe being re-shaped, or by volume rendering the entire volume of the probe being re-shaped.

[00105] As the user changes the shape of the probe, steps 802 through 810 are repeated at a rate sufficiently fast that the user perceives the image of the probe, with texture mapping or volume rendering as appropriate, changing in "real-time" with the changing shape of the probe. The image is being re-drawn at a frame rate sufficiently fast to be perceived as real-time by the user.

[00106] If a user wants to rotate a probe in 3D space, then function **450** is carried out. In function **450**, the 3D orientation, which is the same for both the 3D volume and the probe, is changed, thereby rotating the 3D volume and the probe in space. The steps for carrying out function **450** are shown in FIG. 9 by way of flow diagram connector 9A. In a step 902, the new 3D orientation for the 3D volume and the probe is input by UIM **210** from the user. In a preferred embodiment of the present invention, the user inputs the new orientation by clicking a mouse or other type of suitable user input device to snap a pointer onto an axis of the probe to be rotated. Manipulation of the mouse or user input device changes the orientation of that axis. When the desired orientation is reached, the user again clicks the mouse or user input device to release the pointer from the axis. It would be readily apparent to one of skill in the relevant art how to implement such a change in orientation. It is to be understood, however, that the present invention is not limited to changing the orientation in this manner. For example, the user could select from a number of pre-set rotations (*e.g.*, rotate 90° to the left or right; rotate 45° to the left or right, etc.) by activating a drop-down menu, or by scrolling through the rotations by repeatedly clicking a mouse.

[00107] In a step 904, UIM **210** sends a request to rotate in 3D space to GPM **220** to draw the rotated probe. In a step 906, GPM **220** requests data for the rotated probe from VSM

230. In a manner similar to that described above, the data that is extracted from 3D or data volume **240** by VSM **230** will depend upon the opacity selected by the user for the probe being rotated. If the opacity settings selected by the user are such that all data values for the probe being rotated are opaque, then the data extracted by VSM **230** will be limited to the surfaces of the probe being rotated. Alternatively, if the opacity settings selected by the user for the probe being rotated are such that some of the data values are opaque and some of the data values are transparent, then the data extracted by VSM **230** will include the data corresponding to the entire volume of the probe being rotated. In this manner, the probe can be drawn with its new orientation more quickly by minimizing the quantity of data that must be processed.

[00108] In step 908, GPM **220** processes the data extracted by VSM **230** for the probe being rotated, and draws the probe with its new orientation in accordance with the attributes selected by the user, either by texture mapping onto the surfaces of the probe being rotated, or by volume rendering the entire volume of the probe being rotated.

[00109] As the user rotates the probe in 3D space, steps 902 through 908 are repeated at a rate sufficiently fast that the user perceives the image of the probe, with texture mapping or volume rendering as appropriate, changing in "real-time" with the changing orientation of the probe. The image is being re-drawn at a frame rate sufficiently fast to be perceived as real-time by the user. If a user wants to rotate a probe while it is fixed in 3D space, then function **460** is carried out. In function **460**, the 3D orientation of the probe is rotated independently of the 3D orientation of the 3D volume, thereby rotating the probe while it is fixed in the 3D space defined by the orientation of the 3D volume. In this manner, the

background planes for an active probe can be displayed in a fixed orientation, and the active probe can be rotated within the background planes.

[00110] The steps for carrying out function **460** are shown in FIG. 10 by way of flow diagram connector 10A. In a step 1002, the new 3D orientation for the probe is input by UIM **210** from the user. In a preferred embodiment of the present invention, the user selects the option to rotate while fixed in space, for example, from a "drop-down" menu. The user then inputs the new orientation for the probe by clicking a mouse or other type of suitable user input device to snap a pointer onto an axis of the probe to be rotated. Manipulation of the mouse or user input device changes the orientation of that axis. When the desired orientation is reached, the user again clicks the mouse or user input device to release the pointer from the axis. It would be readily apparent to one of skill in the relevant art how to implement such a change in orientation. It is to be understood, however, that the present invention is not limited to changing the orientation in this manner. For example, the user could select from a number of pre-set rotations (*e.g.*, rotate 90° to the left or right; rotate 45° to the left or right, etc.) by activating a drop-down menu, or by scrolling through the rotations by repeatedly clicking a mouse.

[00111] In a step 1004, UIM **210** sends a request to rotate while fixed in space to GPM **220** to draw the rotated probe. In a step 1006, GPM **220** requests data for the rotated probe from VSM **230**. In a manner similar to that described above, the data that is extracted from 3D or data volume **240** by VSM **230** will depend upon the opacity selected by the user for the probe being rotated. If the opacity settings selected by the user are such that all data values for the probe being rotated are opaque, then the data extracted by VSM **230** will be limited to the surfaces of the probe being rotated.

Alternatively, if the opacity settings selected by the user for the probe being rotated are such that some of the data values are opaque and some of the data values are transparent, then the data extracted by VSM **230** will include the data corresponding to the entire volume of the probe being rotated. In this manner, the probe can be drawn with its new orientation more quickly by minimizing the quantity of data that must be processed.

[00112] In step 1008, GPM **220** processes the data extracted by VSM **230** for the probe being rotated, and draws the probe with its new orientation in accordance with the attributes selected by the user, either by texture mapping onto the surfaces of the probe being rotated, or by volume rendering the entire volume of the probe being rotated.

[00113] As the user rotates the probe while it is fixed in space, steps 1002 through 1008 are repeated at a rate sufficiently fast that the user perceives the image of the probe, with texture mapping or volume rendering as appropriate, changing in "real-time" with the changing orientation of the probe. The image is being re-drawn at a frame rate sufficiently fast to be perceived as real-time by the user.

[00114] If a user wants to carry out an "auto picking" process, then function **470** is carried out. The steps for carrying out function **470** are shown in FIG. 11 by way of flow diagram connector 11A. In a step 1102, a seed point within the data set of the 3D volume, and a selection criteria based on data values, are input by UIM **210** from the user. Preferably the seed point is within the data set of voxels that defines a probe. As described below, such a probe is referred to herein as a seed 3D sampling probe or an eraser 3D sampling probe. However, the seed point can be within the data set of voxels that defines the 3D volume, outside of an active probe. In a preferred embodiment of the

present invention, the user selects the option to execute an auto picking process, for example, from a "drop-down" menu. The user then selects the seed point by clicking a mouse or other type of suitable user input device to snap a pointer onto the desired seed point. The selection criteria can be input, for example, by graphically selecting a range, or by keying in specific numerical values. It would be readily apparent to one of skill in the relevant art how to input from the user a seed point and filter range of data values.

[00115] In a step 1104, UIM **210** sends an auto picking request to GPM **220** to draw the rotated probe. In a step 1106, GPM **220** requests selected points to image from VSM **230**. The selected points are those that are connected to the seed point, and that have a data value within the selection criteria.

[00116] In step 1108, GPM **220** processes the data extracted by VSM **230** to draw the selected points. The selected points are preferably highlighted within the probe by being drawn in a color different from those used to depict the features or physical parameters of the 3D volume data set. Alternatively, step 1108 can be carried out to "erase" or delete from the probe the selected points.

[00117] In a similar manner, auto picking function **470** can be used to "erase" or de-select points. For example, an eraser 3D sampling probe is defined, such as by invoking function **420** to create an additional probe. A "de-selection" criteria based on data values is defined. Points previously selected by an auto picking operation that satisfy the de-selection criteria are identified as candidates for de-selection. As the eraser 3D sampling probe moves through the 3D volume, the de-selected points are deleted from the image, and the image is re-drawn sufficiently fast to be perceived as real-time by the user.

[00118] Once auto picking function **470** is initiated by the user, it can be carried out simultaneously with, for example, move function **430**. In this manner, as the user moves the probe, steps 1102 through 1108 (and steps 702 through 708) are repeated at a rate sufficiently fast that the user perceives the image of the probe, with the selected points, changing in "real-time" with the changing location of the probe. As the probe is moved, the selected points can be highlighted within the probe or within the probe and 3D volume by being drawn in a suitable color, thereby having the auto picking 3D sampling probe function as a "highlighter" as it moves through the 3D volume. Alternatively, as the probe is moved, points previously selected by an auto picking operation can be "erased" or deleted from the probe or the probe and 3D volume, thereby having the probe function as an "eraser" or eraser 3D sampling probe as it moves through the 3D volume. In either embodiment, the image is being re-drawn at a frame rate sufficiently fast to be perceived as real-time by the user.

[00119] With reference now to FIG. 12, one embodiment of a computer system suitable for use with the present invention is shown. A graphics supercomputer **1210** contains one or more central processing units (CPU) or processors **1212**. Supercomputer **1210** contains a random access memory (RAM) **1214** that can be accessed by processors **1212**. Supercomputer **1210** also contains one or more graphics modules **1216** that also access RAM **1214**. Graphics modules **1216** execute the functions carried out by Graphics Processing Module **220**, using hardware (such as specialized graphics processors) or a combination of hardware and software. A user input device **1218** allows a user to control and input information to graphics supercomputer **1210**.

[00120] A particularly preferred graphics supercomputer is an Onyx2 Infinite Reality system, available from Silicon Graphics, Inc., Mountain View, CA, configured with eight processors, three graphics pipelines, 16 GB of main memory, and 250 GB of disk memory. Such a graphics supercomputer has a scalable, high-bandwidth, low-latency architecture to provide high speed rendering on multiple graphics pipelines. Graphics supercomputers from other vendors, such as Hewlett-Packard Company of Palo Alto, CA or Sun Microsystems of Mountain View, CA could also be used.

[00121] The graphics data forming the image to be displayed is sent from graphics supercomputer **1210** to a multiple-screen display system **1220** for projection onto a screen **1230**. In the embodiment shown in FIG. 12, three projectors are used. From the perspective of a user viewing the image on screen **1230**, the three projectors include a left projector **1240**, a center projector **1250**, and a right projector **1260**. Although three projectors are shown, the present invention is not limited to the use of any particular number of projectors.

[00122] Projector **1240** has a projection field on screen **1230**, shown generally at **1242**, between a point **1241** and a point **1243**. Projector **1250** has a projection field on screen **1230**, shown generally at **1252**, between a point **1251** and a point **1253**. Projector **1260** has a projection field on screen **1230**, shown generally at **1262**, between a point **1261** and a point **1263**. Projection fields **1242** and **1252** have an overlap region **1244**, between points **1251** and **1243**. Similarly, projection fields **1262** and **1252** have an overlap region **1264**, between points **1261** and **1253**. The image to be displayed is divided into three (left, center, and right) over-lapping sub-images. By simultaneously projecting the three over-lapping sub-images, the field-of-view to the user is increased over that available, for

example, on a monitor or through the use of just one projector. As an example, use of the three over-lapping sub-images shown in FIG. 12 increases the field-of-view to approximately 160°. Overlap regions **1244** and **1264** are each approximately 5.3°. Multiple-screen display system **1220** accounts for overlap regions **1244** and **1264** in a well-known manner to edge-blend the images of the three projectors to form one seamless image on screen **1230**. Suitable display and projector systems are available from SEOS, London, England, such as the Barco projector units.

[00123] FIG. 13 shows an alternate embodiment of a computer system suitable for use with the present invention. In the embodiment shown in FIG. 13, graphics supercomputer **1210** is configured with multiple processors **1212**, RAM **1214**, and two graphics modules **1216**. Graphics workstations suitable for use in the embodiment shown in FIG. 13 are available from Silicon Graphics, Inc. or Sun Microsystems. Each graphics module **1216** is connected to a monitor **1320** for display. Monitor **1320** should preferably be a color graphics monitor suitable for display of graphics such as that shown in FIGS. 15 and 16. Preferably, one of monitors **1320** displays the image of the 3D sampling probes, and the other of monitors **1320** displays the various menus used to operate 3D sampling probe program **110**. FIG. 13 also shows a keyboard **1330** and a mouse **1332** that function as user input devices.

[00124] A computer system capable of carrying out the functionality described herein is shown in more detail in FIG. 14. Computer system **1402** includes one or more processors, such as processor **1404**. Processor **1404** is connected to a communication bus **1406**. Various software embodiments are described in terms of this exemplary computer system. After reading this description, it will become apparent to a person skilled in the

relevant art how to implement the invention using other computer systems and/or computer architectures.

[00125] Computer system **1402** also includes a main memory **1408**, preferably random access memory (RAM), and can also include a secondary memory **1410**. Secondary memory **1410** can include, for example, a hard disk drive **1412** and/or a removable storage drive **1414**, representing a floppy disk drive, a magnetic tape drive, an optical disk drive, etc. Removable storage drive **1414** reads from and/or writes to a removable storage unit **1418** in a well-known manner. Removable storage unit **1418**, represents a floppy disk, magnetic tape, optical disk, etc. which is read by and written to by removable storage drive **1414**. As will be appreciated, removable storage unit **1418** includes a computer usable storage medium having stored therein computer software and/or data.

[00126] In alternative embodiments, secondary memory **1410** may include other similar means for allowing computer programs or other instructions to be loaded into computer system **1402**. Such means can include, for example, a removable storage unit **1422** and an interface **1420**. Examples of such can include a program cartridge and cartridge interface (such as that found in video game devices), a removable memory chip (such as an EPROM, or PROM) and associated socket, and other removable storage units **1422** and interfaces **1420** which allow software and data to be transferred from removable storage unit **1422** to computer system **1402**.

[00127] Computer system **1402** can also include a communications interface **1424**. Communications interface **1424** allows software and data to be transferred between

computer system **1402** and external devices. Examples of communications interface **1424** can include a modem, a network interface (such as an Ethernet card), a communications port, a PCMCIA slot and card, etc. Software and data transferred via communications interface **1424** are in the form of signals **1426** that can be electronic, electromagnetic, optical or other signals capable of being received by communications interface **1424**. Signals **1426** are provided to communications interface via a channel **1428**. Channel **1428** carries signals **1426** and can be implemented using wire or cable, fiber optics, a phone line, a cellular phone link, an RF link and other communications channels.

[00128] In this document, the terms "computer program medium" and "computer usable medium" are used to generally refer to media such as removable storage device **1418**, a hard disk installed in hard disk drive **1412**, and signals **1426**. These computer program products are means for providing software to computer system **1402**.

[00129] Computer programs (also called computer control logic) are stored in main memory **1408** and/or secondary memory **1410**. Computer programs can also be received via communications interface **1424**. Such computer programs, when executed, enable computer system **1402** to perform the features of the present invention as discussed herein. In particular, the computer programs, when executed, enable processor **1404** to perform the features of the present invention. Accordingly, such computer programs represent controllers of computer system **1402**.

[00130] In an embodiment where the invention is implemented using software, the software may be stored in a computer program product and loaded into computer system **1402** using removable storage drive **1414**, hard drive **1412** or communications interface

1424. The control logic (software), when executed by processor **1404**, causes processor **1404** to perform the functions of the invention as described herein.

[00131] In another embodiment, the invention is implemented primarily in hardware using, for example, hardware components such as application specific integrated circuits (ASICs). Implementation of such a hardware state machine so as to perform the functions described herein will be apparent to persons skilled in the relevant art(s).

[00132] In yet another embodiment, the invention is implemented using a combination of both hardware and software.

System Operation and Results

[00133] The operation and results of the present invention will now be described, using a data volume **240** that contains seismic data (data values representing seismic amplitudes). The user specifies the particular seismic data volume to be used, which is loaded from disk into main memory. A default 3D sampling probe is drawn. The user specifies the colors to be used for the seismic amplitudes, such as the red, blue, and white shown in FIGS. 15 and 16. The degree of transparency can also be selected. The three probes shown in FIG. 15 are all opaque, with the intersection of the probes and the seismic data volume texture mapped onto the surfaces of the probes. One of the probes is displayed with the bounding geometry shown; the other two probes are displayed without the bounding geometry.

[00134] FIG. 15 shows three active probes. The user has selected not to display the data contained in the background planes and in the remainder of the seismic data volume outside of the active probes. Two of the probes shown in FIG. 15 intersect each other,

and the intersection of the two probes is displayed. In this manner, the user can more readily visualize and interpret geologic features inherent in the seismic data volume. For example, a geologic feature, represented by a dark red band between two light blue bands, extends across the face of the larger intersecting probe and "turns the corner" to extend onto the face of the smaller intersecting probe perpendicular to it. The ability to move and intersect the probes with each other, and throughout the seismic data volume, enables a user to better interpret and track the extent of such a geologic feature.

[00135] FIG. 16 illustrates how one probe can be used to "cut" another probe to create a "hole" in a probe. As with FIG. 15, the user has selected not to display the data contained in the background planes and in the remainder of the seismic data volume outside of the active probes. FIG. 16 illustrates that the opacity settings can be individually selected by the user for each active probe. One of the probes shown in FIG. 16 is opaque, so that it is not possible to see through the surfaces of this probe. In order to see internal to this outer probe, it must be cut away by another probe. The outer opaque probe is referred to as a "data probe". A second completely transparent "cut probe" has been used to cut out a 3D sub-section of the data probe. Because the cut probe is completely transparent, it is not visible in FIG. 16. However, the fact that the completely transparent cut probe is present is evidenced by the fact that the opaque internal surfaces of the data probe are visible. The image of the intersection of the data probe and the cut probe is the intersecting surface internal to the data probe.

[00136] A third active probe is shown in FIG. 16. The third probe is displayed with the bounding geometry shown. The third probe is volume rendered with varying degrees of transparency so that the user can see through the outer surfaces of the probe and view

geologic features within the third probe. As shown in FIG. 16, the third probe is volume rendered partially within the 3D sub-section of the data probe that has been cut away by the cut probe.

[00137] The third volume-rendered probe shown in FIG. 16 also contains selected points that have been selected through a seed picking process (function 470). The selected points have been imaged in a manner to highlight them for the user. The selected points are shown in FIG. 16 as the yellow highlighted points. The seed point is illustrated in FIG. 16 by the darker sphere.

[00138] By using the system and method of the present invention, geologists and geophysicists can more quickly and accurately visualize and interpret 3D seismic data. This sharply reduces 3D seismic project cycle time, boosts production from existing fields, and finds more reserves.

Conclusion

[00139] While various embodiments of the present invention have been described above, it should be understood that they have been presented by way of example only, and not limitation. Thus, the breadth and scope of the present invention should not be limited by any of the above described exemplary embodiments, but should be defined only in accordance with the following claims and their equivalents.